Perceptual Compensation for Voice Assimilation of German Fricatives

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Abstract

In German, word-initial lax fricatives may be produced with substantially reduced glottal vibration after voiceless obstruents. This assimilation occurs more frequently and to a larger extent across prosodic word boundaries than across phrase boundaries. Assimilatory devoicing makes the fricatives more similar to their tense counterparts and could thus hinder word recognition. The present study investigates how listeners cope with assimilatory devoicing. Results of a cross-modal priming experiment indicate that listeners compensate for assimilation in appropriate contexts. Prosodic structure moderates compensation for assimilation: Compensation occurs especially after phrase boundaries, where devoiced fricatives are sufficiently long to be confused with their tense counterparts.

1. Introduction

Assimilation contributes substantially to the variance in spoken language. As a consequence, it causes a potential challenge for word recognition, since listeners must map different word forms to the same lexical representation. There are several solutions to this problem. First, it is known that listeners compensate for assimilation by adapting their phoneme categories to segmental contexts. In contexts that license assimilation (viable contexts), phonological feature changes in the assimilated speech sounds are easily tolerated, whereas such changes seriously hinder the recognition of the intended word in environments that do not license the assimilation (non-viable contexts; e.g., Gaskell & Marslen-Wilson 1996; Coenen, Zwitserlood & Bölte 2001; Gow 2003; Mitterer & Blomert 2003). Second, assimilation is often gradient rather than categorical, whereby the acoustic details of assimilated word forms preserve cues to the underlying form. Listeners take advantage of such fine phonetic detail (Gow 2003; Nolan 1992; Snoeren, Hallé & Segui, in press). Finally, assimilation is constrained by prosodic structure: Larger prosodic boundaries inhibit the occurrence and degree of assimilation (Nespor & Vogel 1986; Kuzla, Cho & Ernestus, in press), which is in line with phonetic research on the articulatory strengthening of segments in prominent prosodic positions, in particular at the beginning of prosodic domains (Keating, Cho, Fougeron & Hsu 2003). A prosodic analysis of the spoken utterance may help listeners to identify a word form as assimilated or not.

In German, fricatives can be devoiced after voiceless obstruents, even across word boundaries (Kohler 1995; Jessen 1998). As a result, assimilated fricatives can become more similar to their voiceless counterparts, leading to increased ambiguity for minimal pairs such as /vaɪn/ *Wein* ‘wine’ and /faɪn/ *fein* ‘fine’. Kuzla, Cho & Ernestus (in press) showed that this assimilation is graded and conditioned by prosodic structure, such that fricatives are devoiced more often and to a greater extent after prosodic word boundaries than after prosodic phrase boundaries. Importantly, even complete devoicing does not lead to neutralization of the tense-lax contrast, since other cues to this contrast are not affected. For instance, a completely devoiced /v/ is still differentiated from /f/ by its shorter duration.

Despite the overall maintenance of phonological contrasts, the question remains whether listeners are sensitive to the systematic variation in glottal vibration, one of the major cues to laxness. Compensation for assimilation predicts that a devoiced /v/ should be perceived as less similar to /f/ in assimilation contexts than in non-assimilation contexts. Moderation of this compensation by prosodic structure would imply that a devoiced /v/ is perceived as more similar to /f/ after phrase boundaries than after word boundaries, because assimilatory devoicing is less frequent and often incomplete in this prosodic position. Using an off-line phoneme categorization task, Kuzla, Ernestus & Mitterer (in press) found that listeners’ compensation

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for assimilatory devoicing is indeed moderated by these prosodic effects if other cues (e.g., duration, frication energy) are covaried with the amount of glottal vibration during the fricative. If these secondary cues remain consistent with the lax fricative /v/, there is generally little confusability with /f/. Nevertheless, compensation for assimilation still occurs: more /v/-responses are obtained in assimilation context than in non-assimilation context. This context effect is larger after a prosodic phrase boundary, where fricatives are longer than they are after a word boundary. This suggests that the durational cue to laxness preserved in the fine phonetic detail of the assimilated fricative is more informative in the Word condition than in the Phrase condition.

The goal of the present study is to further investigate the role of phonetic detail in combination with segmental and prosodic context in the perception of devoiced fricatives. In contrast to Kuzla, Ernestus and Mitterer (in press), we use an online task, in order to get better insight into the early processes of compensation for assimilation.

2. Experiment

We used cross-modal identity priming to examine this issue. In this task, participants have to decide whether a visually presented target word is an existing word or not (lexical decision) shortly after they have heard an auditory stimulus (the prime). Reaction times are typically faster if the target word has been heard shortly before. Responses are slower if a competing word has been presented. If one member of a minimal pair is used as the target, this task allows us to investigate whether an auditorily presented form is perceived as different or similar to that member, as a function of segmental and prosodic contexts.

We tested the following two hypotheses. First, we predicted that a devoiced /v/ in /vaɪn/ *Wein* 'wine' primes /faɪn/ *fein* 'fine' in non-assimilation context, where devoiced /v/ typically does not occur and therefore may be interpreted as /f/. In contrast, devoiced /v/ should not prime, or even inhibit, /faɪn/ in assimilation context, since devoiced /v/ may be the assimilated form of /v/ from /vaɪn/ (Compensation for Assimilation Hypothesis). Second, we expected these differences in priming to be stronger after a prosodic phrase boundary than after a word boundary, because complete devoicing is less natural after a Phrase boundary in production, and because other phonetic cues to /v/ (e.g., duration) may be less salient in this prosodic position, so that listeners have to rely on context more (Prosodic Structure Hypothesis).

2.1. Materials and Design

Fifty minimal pairs of German mono- and bisyllabic words were selected (see Appendix). The members of the pairs differed in the phonological voicing of their initial labiodental fricative, as in /vaɪn/ *Wein* 'wine' versus /faɪn/ *fein* 'fine'. The prime words appeared in semantically neutral sentence contexts, which biased neither the /v/- nor the /f/- initial words. The /f/-initial members of the minimal pairs served as targets in the visual lexical decision task, and also as prime words in the Identity condition. The corresponding /v/-initial words were the auditory prime words in our four experimental conditions. For these conditions, the context before the prime words (referred to as the pre-prime in the following) contained the manipulation of two experimental factors: Immediately preceding segmental context (/ə/ versus /t/; i.e., viable versus non-viable assimilation context), and prosody (Word boundary versus Phrase boundary). The crossing of these two factors Context and Prosody yielded four experimental conditions (Word_e, Word_t, Phrase_e, and Phrase_t). In the Word_e condition, the prime word was preceded by /ə/ from *hatte* 'had' (non-viable assimilation context), and a prosodic word boundary (Example 1). The Word_t condition was the same except that the preceding segment was /t/ from *hat* 'has' (viable assimilation context, triggering devoicing). In the Phrase_e condition, the preceding segment was /ə/ from *vorhatte* 'wanted', but the prosodic boundary was a phrase boundary. Phonetically, the phrase boundary was characterized by preboundary lengthening and an intonation rise ('high boundary tone'). In the fourth condition, Phrase_t, the context was /t/ from *vorhat* '(she) wants' before a Phrase boundary (Example 2).

(1) *Anna hatte Wein richtig geschrieben.*
'Anna had written wine correctly'.

(2) *Weil sie vorhat, Wein richtig zu schreiben, fragt sie Paul.*
'Since she wants to write wine correctly, she asks Paul.'

Fifty phonologically unrelated words were selected as prime words for a control condition (the Unrelated condition). In addition, the experiment contained 150 fillers of three types, 50 of each type.
For filler Type A, prime words were 25 /v/-initial and 25 /f/-initial words which do not form minimal pairs with existing /f/- respectively /v/-initial words (e.g., *Waffel* 'wafer', **Faffel; Fabel* 'fairy tale', *Wabel). The targets were 50 non-words. Primes in the fillers of Type B were phonologically unrelated words, and targets were again non-words. Type C fillers consisted of phonologically unrelated prime words and unrelated existing target words. The total numbers of Yes/No

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responses in the lexical decision task were equal. For the Identity and the Unrelated condition and for all fillers, the characteristics of the carrier sentences varied between the four segmental and prosodic conditions used in the experimental conditions. Table 1 provides an overview of the stimulus structure for all conditions and fillers with examples.

Condition	Pre-prime	Prime word	Post-prime	Target
Identity	varying	*fein* 'fine'	varying	fein 'fine'
Unrelated		*Biene* 'bee'		
Word_e	*Anna hatte_*	*Wein* 'wine'	*_richtig geschrieben*	
Word_t	*Anna hat_*			
Phrase_e	*Weil sie vorhatte,_*		*_richtig zu schreiben, fragt sie Paul*	
Phrase_t	*Weil sie vorhat,_*			
Filler	varying	*Waffel* 'wafer' (*Faffel)	varying	Non-word
Type A				
Type B		*Biene* 'bee'		
Type C				Hand 'hand'

Table 1: Stimulus structure

In addition, 20 catch trials were randomly inserted in the experiment to ensure that participants paid attention to the auditory stimuli. In these trials, participants had to answer a Yes/No question about the prime sentence (e.g., 'Was it Anna who wrote wine correctly?') instead of performing lexical decision on the target. For this purpose, the proper names in the carrier sentences were varied between eight bisyllabic female names in the pre-primes of the Word conditions and eight monosyllabic male names in the post-primes of the Phrase conditions.

A female native speaker of German read several repetitions of the materials in a sound-attenuated booth. Recordings were made with a Sennheiser microphone, and directly stored onto a computer, at a sample rate of 48 kHz. From these recordings, we selected one realization of

- each pre-prime carrier sentence,
- each /f/-prime word,
- each unrelated prime word,
- each filler prime word,
- each post-prime carrier sentence,
- each /v/-prime word from a Word_e context, and
- each /v/-prime word from a Phrase_e context.

What is important to note here is that we selected two prosodically different realizations of the /v/-prime words because the acoustic details of domain-initial words are known to be affected by the prosodic hierarchy (e.g., Keating et al. 2003).

To investigate the perceptual effects of devoicing, the initial fricatives of all /v/-prime words within the same prosodic category were replaced by an identical acoustic sound. For the Word conditions, we resynthesized a completely voiceless /v/ produced by our speaker in assimilation context during the recording. This sound had a duration of 50 ms. The sound used in the Phrase conditions was created by expanding the duration of the sound from the Word conditions to 70 ms. These two durations are typical for the two prosodic domains for our speaker. The speech editing was done with the PSOLA component of the PRAAT software package (Boersma 2001). The selected recordings of the pre-primes, the prime words and the post-primes were combined online during the experiment to form the auditory stimuli of the respective conditions.

In order to ensure sufficient statistical power despite the limited number of items, two versions of the experiment were created. Context was treated as a within-subjects factor, and Prosody as a between-subjects factor. Version 1 of the experiment contained the Word_e condition, the Word_t condition, the Identity condition, and the Unrelated condition. Version 2 contained the Phrase_e condition, the Phrase_t condition, the Identity, and the Unrelated condition. Moreover, each version of the experiment contained an additional condition testing for factors not reported in the present paper. The priming conditions in both versions were counterbalanced across five different lists, and each participant saw each target only once. Each list contained 224 trials: four training trials, the 50 experimental trials, 150 fillers, and 20 catch trials.

2.2. Participants

One hundred native listeners of German participated in the experiment for a small payment. Most of them were students at Kiel University, and none of them reported any hearing disorders. Half of them received the Word version of the experiment, and the other half the Phrase version.

2.3. Procedure

Participants were tested one by one in a quiet room by means of a portable computer. They were instructed to listen to the auditory primes and to decide as quickly as possible whether the stimulus appearing on the computer screen was an existing word or not. Furthermore, participants were told that occasionally they would have to answer a written question about the

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sentence they had just heard. Participants indicated their lexical decisions and answers to the questions by pressing one out of two response buttons. The experiment was controlled by NESU (=Nijmegen Experimental Set-Up) software. The auditory primes were presented at a comfortable listening level via headphones. The visual targets appeared in a large font on the computer screen half a prime word duration after offset of the prime word, i.e., during the post-prime part of the auditory prime. This ensured that listeners had heard the prosodic information spread over the pre-prime and the prime word when the target appeared. After each block of 50 trials participants were allowed to take a short break. An experimental session lasted about 30 minutes.

2.4. Results and Discussion

Mean reaction times of the correct responses to the /f/-initial target words per condition are shown in Table 2. RTs below 400 ms and above 1500 ms were discarded. For all analyses, we fitted linear mixed-effects (lme) models with Participant and Item as random factors (Pinheiro & Bates 2000; Baayen 2004). RTs were logarithmically transformed into lnRT to obtain a quasi-normal distribution of this dependent variable.

Condition (prime)	Mean RT [ms]
Identity	794
Unrelated	832
Word_e (non-assim.)	847
Word_t (assim.)	837
Phrase_e (non-assim.)	833
Phrase_t (assim.)	859

Table 2: Mean reaction times in ms per condition

First, we examined the conditions that appeared in both versions of the experiment, that is, the Identity condition and the Unrelated condition. An analysis of lnRTs in these two conditions with Condition and Experiment Version as fixed factors yielded a significant effect of condition ($F(1, 1713) = 33.30$, $p < 0.001$), that is, facilitation in the Identity condition. There was neither a main effect of Experiment Version nor an interaction of Condition with Experiment Version. These results allowed us to pool the data from the two experimental groups for further analysis.

To examine the effects of segmental context and prosodic structure on the perception of devoiced fricatives, we restricted the dataset to the experimental conditions (Word_e, Word_t, Phrase_e and Phrase_t). We analyzed lnRT as function of Prosody (Word, Phrase), Context (e, t), and Trial Number. Trial Number was included in the model as a covariate, since participants might have become faster or slower during the experiment as a consequence of practice or fatigue. Trial Number was significant (faster responses with increasing Trial Number, $F(1, 1607) = 156.59$, $p < 0.001$), as it was in both of the following separate analyses, but there were no significant interactions involving this factor. Neither Prosody ($F(1, 1607) = 0.10$, $p = 0.75$) nor Context ($F(1, 1607) = 1.19$, $p = 0.28$) emerged as significant; however, there was a significant interaction of these two factors ($F(1, 1607) = 6.11$, $p < 0.05$). In order to investigate the interaction, we split the data by Prosody and modeled the lnRT as a function of Context and Trial Number. After a Word boundary, there was no effect of context ($F(1, 849) = 0.48$, $p = 0.49$). In contrast, after a Phrase boundary, Context was significant ($F(1,758) = 4.47$, $p < 0.05$), indicating faster RTs in the non-assimilation (/ə/-) context than in the assimilation (/t/-) context.

Finally, posthoc Bonferroni comparisons were carried out between the four experimental conditions and the unrelated conditions in the respective versions of the experiment. These comparisons revealed a significant difference between the Phrase_t condition and the unrelated condition, indicating inhibition, whereas the other conditions did not differ from the Unrelated condition. These findings are in line with the difference found between Phrase_t and Phrase_e in the previous analysis. In addition, posthoc comparisons with Bonferroni adjustments showed that the Identity condition differed significantly from all experimental conditions (all $p < 0.001$). The priming effects can be seen in Figure 1. The pattern shows that a devoiced /v/ never leads to equally fast responses as the identity prime-word starting with /f/, but that, surprisingly, only in Phrase_t, there is significant inhibition.

These results partly confirm our hypotheses. As predicted by the Compensation for Assimilation Hypothesis, there is an effect of context, but only after a Phrase boundary. However, this is evidence for the expected difference between the prosodic conditions (Prosodic Structure Hypothesis).

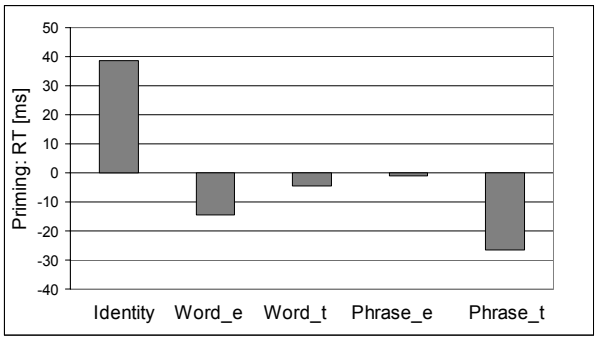

Figure 1: Priming results computed as the difference between RTs in the conditions on the x-axis and in the unrelated control condition, with a positive value indicating facilitation and a negative inhibition

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3. General Discussion

This study investigated the role of context and prosodic boundary size in the perception of devoiced fricatives at word onsets in German. Lax fricatives such as /v/ can be devoiced after voiceless obstruents (Kohler 1995, Jessen 1998). This assimilation occurs more frequently and to a larger extent across smaller prosodic boundaries (Kuzla, Cho & Ernestus, in press). Devoicing affects an important cue to the phonological tense-lax contrast in minimal pairs such as /vaɪn/ *Wein* 'wine' and /faɪn/ *fein* 'fine'.

We examined how segmental context and prosodic structure influenced the perception of a devoiced fricative as /v/ or /f/ in a cross-modal priming experiment with the /f/-initial words as targets. Responses to these targets should be faster the more similar an auditory prime is to the target.

A study by Alphen & McQueen (2006) applied a similar method investigating the role of prevoicing in Dutch word-initial stops. These authors found that making a lax stop (normally prevoiced) more tense-like by removing the prevoicing influences the lexical activation of competing words starting with a voiceless plosive. Similarly, Andruski, Blumstein & Burton (1994) reported in a study on the effects of fine phonetic detail (Voice Onset Time) of English stops that phonologically similar competitor word candidates are activated in a graded fashion, depending on the subphonemic acoustic shape of the prime words.

In our experiment, as expected, there was significant identity priming, i.e., facilitation if the /f/-initial word had been heard as a prime. We hypothesized that the segmental context would influence the perception of a devoiced fricative, i.e., that it would be recognized as /v/ more easily in assimilation that in non-assimilation context. This hypothesis was partly confirmed, as the predicted effect was observed after a Phrase boundary, but not after a Word boundary. The difference between the two prosodic boundary conditions, however, confirms our second hypothesis that compensation for assimilation would be modulated by prosodic structure. After a prosodic word boundary, we did not find any effect of context, neither priming nor inhibition. In contrast, after a phrase boundary, there was inhibition in assimilation context, but not in non-assimilation context. We take this as evidence for compensation for assimilation. However, there was again no priming in the non-assimilation context. The lack of priming in assimilation context after both prosodic boundaries indicates that there are always sufficient secondary cues that distinguish a devoiced /v/ from /f/. After word boundaries, these other cues (e.g., duration) leave no role for compensation for assimilation. After phrase boundaries, the fricative is longer than after word boundaries, and this longer duration appears to increase the ambiguity between a devoiced /v/ and /f/; hence listeners take the context into account and compensate for assimilation. In the non-assimilation context, the mismatch between the segmental environment and the voicing characteristics of the fricative in the prime leads to faster responses to the /f/-targets than in the assimilation context. Apparently, there is less competition from the prime. That the reaction times are nevertheless not as fast as if the listeners had heard a genuine /f/ suggests that the prime is perceived as intermediate between /v/ and /f/. Together, the results of our study indicate that segmental context, fine phonetic detail and prosodic structure interact in a complex way in on-line recognition of spoken words.

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Appendix: Minimal Pairs

v-prime words		**f-prime words/targets**	
wach	*awake*	Fach	*partition*
Wachmann	*guard*	Fachmann	*expert*
wackeln	*to shake*	Fackeln	*to hesitate*
Waden	*calves*	Faden	*thread*
wäre	*were*	Fähre	*ferry*
Werte	*values*	Fährte	*track*
wellig	*wavy*	Fällig	*due*
Welt	*world*	Fällt	*falls*
werben	*to advertise*	Färben	*to colour*
wahren	*to keep*	Fahren	*to drive*
warten	*to wait*	Fahrten	*rides*
Wall	*dam*	Fall	*fall*
Walter	*(proper name)*	Falter	*butterfly*
Wand	*wall*	Fand	*found*
Wangen	*cheeks*	Fangen	*to catch*
warm	*warm*	Farm	*farm*
was	*what*	Fass	*barrel*
wachsen	*to grow*	Faxen	*to fax*
Wächter	*guard*	Fechter	*fencer*
weder	*neither*	Feder	*feather*
wehen	*to blow*	Feen	*fairies*
Wege	*ways*	Fege	*sweep*
Wähler	*voter*	Fehler	*error*
Weiher	*pond*	Feier	*party*
Weile	*while*	Feile	*file*
Wein	*wine*	Fein	*fine*
Wälder	*forests*	Felder	*fields*
Welle	*wave*	Felle	*furs*
Werner	*(proper name)*	Ferner	*further*
Weste	*waistcoat*	Feste	*festivities*
wetten	*to bet*	Fetten	*to grease*
wetzen	*to sharpen*	Fetzen	*rag*
Wichte	*wights*	Fichte	*spruce*
Wiese	*meadow*	Fiese	*nasty (pl)*
winden	*to wind*	Finden	*to find*
winken	*to wave*	Finken	*finches*
wischen	*to wipe*	Fischen	*to fish*
Wort	*word*	Fort	*away*
Wrack	*wreck*	Frack	*dress-coat*
Wuchs	*growth*	Fuchs	*fox*
wühlen	*to dig*	Fühlen	*to feel*
Wunde	*wound*	Funde	*findings*
Vase	*vase*	Phase	*phase*
Weilchen	*while dim.*	Veilchen	*violet*
Wetter	*weather*	Vetter	*cousin*
wir	*we*	Vier	*four*
Wolke	*cloud*	Volke	*people (infl)*
Wolle	*wool*	volle	*full (infl)*
Wok	*wok*	Fock	*foresail*
wedeln	*to fan*	fädeln	*to thread*

(dim.= diminutive; infl. = inflected form)

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